Modelling the ISM in Star Forming Galaxies

Evolution of Large and Small Scale Structures

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Overview

- Introduction
- High Resolution Simulations of ISM: HD and MHD
  - Large Scale Structure: Fountain Flow
  - Small Scale Structure: Filaments and SCL's
- Results
  - Comparison to observations:
    - Volume filling factors, OVI column densities,
    - Chandrasekhar-Fermi law, Stability of gas phases
  - Some Characteristics of ISM Turbulence
  - Local ISM (Local Bubble)
- Summary & Conclusions

Introduction

- Spitzer image of LMC (Credit: NASA/JPL)
- 10^6 objects in the IR
- Diffuse emission from dust

- Low resolution: ISM appears smooth and distributed into distinct phases: molecular (MM), cold (CNM), warm (WNM + WIM: neutral + ionized), hot (HIM)
- High resolution: ISM is frothy, filamentary, fractal, not in pressure equilibrium, turbulent (supersonic, superalfvénic)

→ Models like 3-phase (McKee & Ostriker 1977) and "chimney" model (Norman & Ikeuchi 1989) capture some structure but not the essential physics

Standard ISM picture:

McKee & Ostriker, 1977

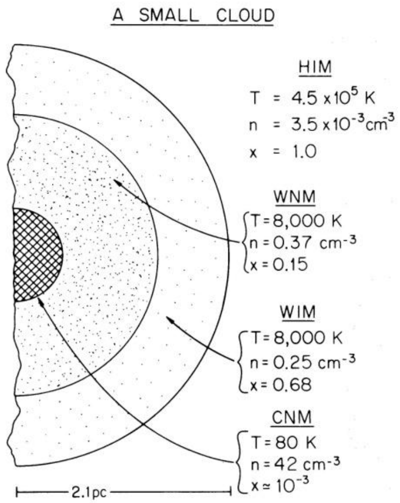


FIG. 1

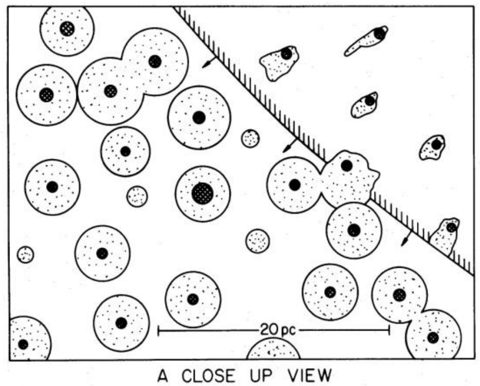


FIG. 2

FIG. 1.—Cross section of a characteristic small cloud. The crosshatched region shows the cold core, which gives the usual optical absorption lines. Next is the warm neutral medium (WNM) with ionization produced by soft X-ray background. The outer layer (WIM) is gas largely ionized by stellar UV background. Typical values of hydrogen density n, temperature T, and ionization $x = n_e/n$ are shown for each component, except that a higher than average value of the soft X-ray flux has been assumed in order to produce a significant amount of WNM at this pressure.

FIG. 2.—Small-scale structure of the interstellar medium. A cross section of a representative region 30 pc × 40 pc in extent is shown, with the area of the features being approximately proportional to their filling factors. A supernova blast wave is expanding into the region from the upper right. The radius of the neutral cores of the clouds (represented by crosshatching) ranges from about 0.4 to 1 pc in this small region; all the clouds with cores have warm envelopes (*dotted regions*) of radius $a_w \sim 2.1$ pc. A few clouds are too small to have cores. The envelopes of clouds inside the SNR are compressed and distorted.

- ~50% of WNM is unstable (Heiles 2001, Heiles & Troland 2003)
- global pressure equilibrium does not exist: 500 < P/k < 4000 K cm-3 (Jenkins & Tripp 2006)

3-phase ISM (MO77)

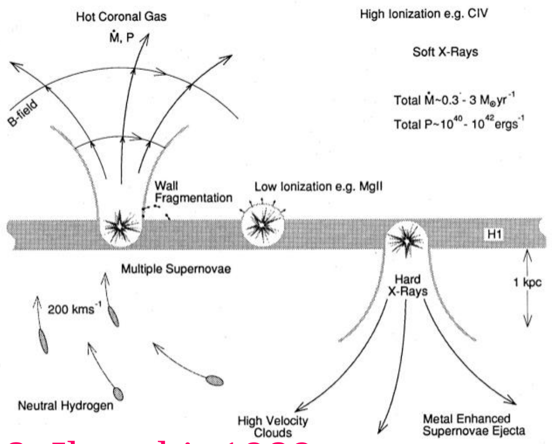
- overall pervasive HIM: $(n,T) = (10^{-2.5}\ cm^{-3}, 10^{5.7}\ K)$ regulated by SNe: $f_V \sim 0.5$-0.7
- HIM interspersed with clouds
- clouds consist of envelopes of CNM, WNM, WIM

Problems:

- SNe occur partly in clusters
- $f_V \sim 0.2 - 0.3$
- DIG not predicted
- more WNM than predicted
- CNM is mostly in filaments not in clouds

Improvements:

No. 1, 1989 DISK-HALO INTERACTION 381



Norman & Ikeuchi, 1989

HALO STRUCTURE

FIG. 5.—A sketch of some of the obvious qualitative aspects of the halo structure in the chimney model. The observational characteristics and effects on galaxy evolution of these disk-halo connections are discussed in §§ IV and V.

SB blow-/break-out into halo

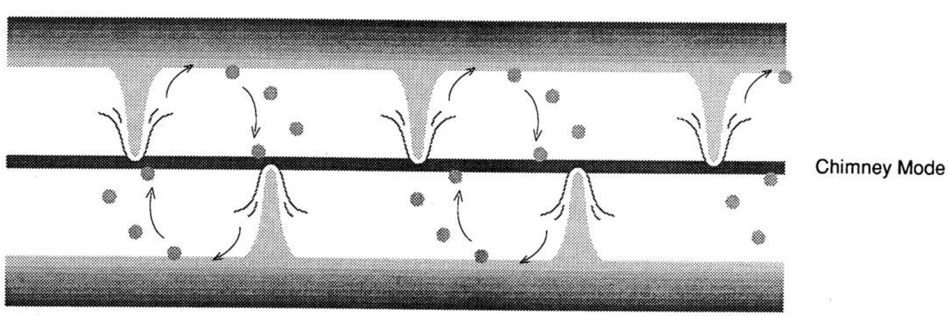


FIG. 4b

"clustered" fountain

Chimney Model (NI 89)

- superbubble expansion is dominating random SNRs
- disk-halo interaction is taken into account ("break-out")
- localized galactic fountain established
- f_V(HIM) ~ 0.3 – 0.4

Problems:

- constant ambient density unrealistic for SB evolution
- SB break-out dynamics fishy
- stability of phases? (e.g. 50% of WNM unstable)

- Reynolds Number is high: $Re = \frac{uL}{\nu} \approx 3\times 10^3 M\; L[pc]\, n[cm^{-3}]$

  i.e. $10^5 - 10^7$ (Elmegreen & Scalo 2004); M=u/c … Mach number

→ ISM is highly turbulent and compressible!
(predicted already by C.F. v. Weizsäcker, 1951)

- Possible driving sources:
  - stellar: HII regions, stellar winds, supernovae (SNe), superbubbles (SBs)
  - galactic rotation
  - self-gravity
  - fluid instabilities: RT-, KH-, Parker instability, MRI etc.
  - MHD: streaming instability (cosmic rays)

SNe dominate energy input in spirals (Mac Low & Klessen 2004):

$$\frac{dE}{dt} \cong -\frac{1}{2}\rho\frac{v_{rms}^3}{L_0} \approx 3\times 10^{-26}\left(\frac{\eta_{SN}}{0.1}\right)\left(\frac{\sigma_{SN}}{1\mathrm{SNu}}\right)\left(\frac{H_c}{100\mathrm{pc}}\right)^{-1}\left(\frac{R_{SF}}{15\mathrm{kpc}}\right)^{-2}\left(\frac{E_{SN}}{10^{51}\mathrm{erg}}\right)\ \mathrm{erg\ cm^{-3}\ s^{-1}}$$

Modeling a SN driven ISM

Things to remember:

- choose a "representative" patch of the ISM
  - large enough to be not severely influenced by BC's
  - small enough to put on a grid with sufficient resolution
- choose a sufficiently large extension perpendicular to the disk to capture disk-halo-disk circulation flows
- Evolution time: results should not depend on initial set-up: erase "memory effects"

Philosophy: "bottom-up" model

- include physical processes step by step
- focus on the most important ones:
  → heating and cooling
  → gravitational potential by stars (self-gravity in some sims.)
  → galactic magnetic field and its evolution

High Resolution Simulations

- Solve full-blown HD/MHD equations on a
  large grid: 1 kpc × 1kpc × ± 10 kpc (Δx=0.625 pc)
- Type Ia,b/II SNe: random + clustered (~60%), IMF
- Background heating due to diffuse UV photon field
- SFR ∝ local density/temp.: n >10 cm^{-3}/T≤100 K

  ⟹ formation and motion of OB associations (v_{rms} ~ 5 km/s)
- Evolution of computational volume for τ ~ 400 Myr

  ⟹ sufficiently long to erase memory of initial conditions
- Galactic gravitational field by stars (Kuijken & Gilmore, 1989)
- 3D calculations on parallel processors with AMR

Equations

- HD/MHD system

$$\frac{\partial \rho}{\partial t} + \nabla(\rho\,\vec{u}) = q$$ Mass conservation

$$\frac{\partial(\rho\,\vec{u})}{\partial t} + \nabla(\overleftrightarrow{T}) = \rho\,\vec{F} + \vec{m}$$ Momentum conservation

$$\frac{\partial\,W}{\partial\,t} + \nabla\vec{S} = \rho\,\vec{u}\,(\vec{F} + \vec{m}) + \dot{W}_0$$ Energy conservation

$$\vec{E} = -\frac{1}{c}(\vec{u}\times\vec{B})$$

Maxwell Eqs.
(ideal MHD)

$$\frac{\partial\,\vec{B}}{\partial\,t} = -c\,(\nabla\times\vec{E})$$ (with $\nabla\,\vec{B} = 0$ as initial condition!)

with

$$\overleftrightarrow{T} = \rho\, \vec{u} \otimes \vec{u} + \left[P_g + \frac{B^2}{8\pi} \right] \bullet \overleftrightarrow{I} - \frac{\vec{B} \otimes \vec{B}}{4\pi}$$

Momentum flux density tensor

$$W = \frac{1}{2} \rho\, u^2 + \frac{P_g}{\gamma_g - 1} + \frac{B^2}{8\pi}$$

Total energy density

$$\vec{S} = \left(\frac{1}{2} u^2 + \frac{\gamma_g}{\gamma_g - 1} \frac{P_g}{\rho} \right) \rho\, \vec{u} + \frac{\vec{E} \times \vec{B}}{4\pi}$$

Energy flux density

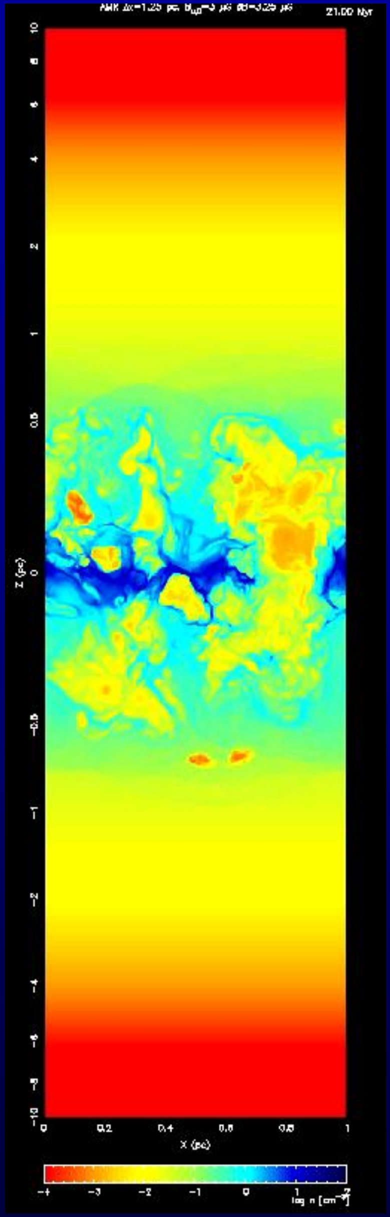
Boundary conditions: mass, momentum and energy input from SNRs/SBs:

Source terms: $q=M_{ej}/(V_{ej}\, t_0)$, $m=qu_{ej}$, $dW_0/dt=(W_{k0}+W_{th})/t_0$

gravitational force: $F=-\nabla\Phi$; background heating (Wolfire et al. 1995)

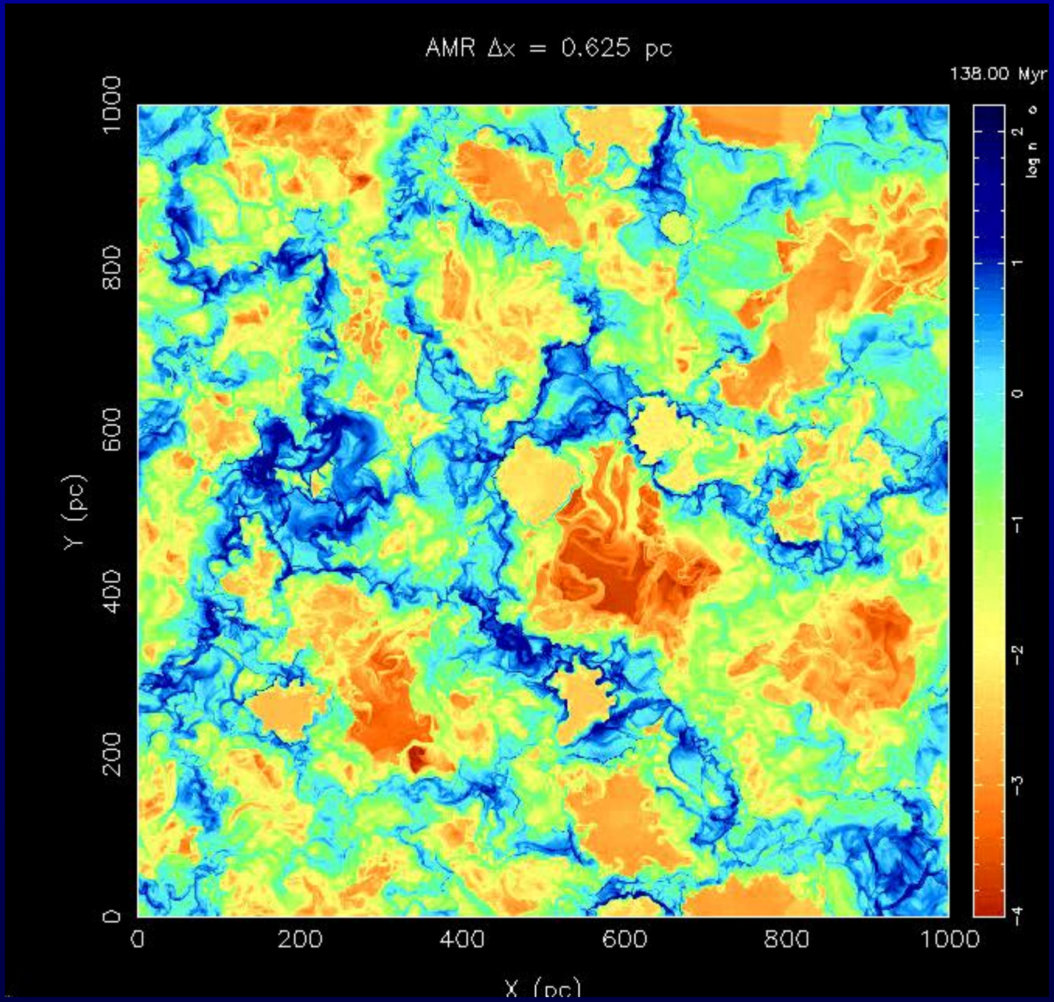
HD Evolution of large/small scale structures of the ISM

z

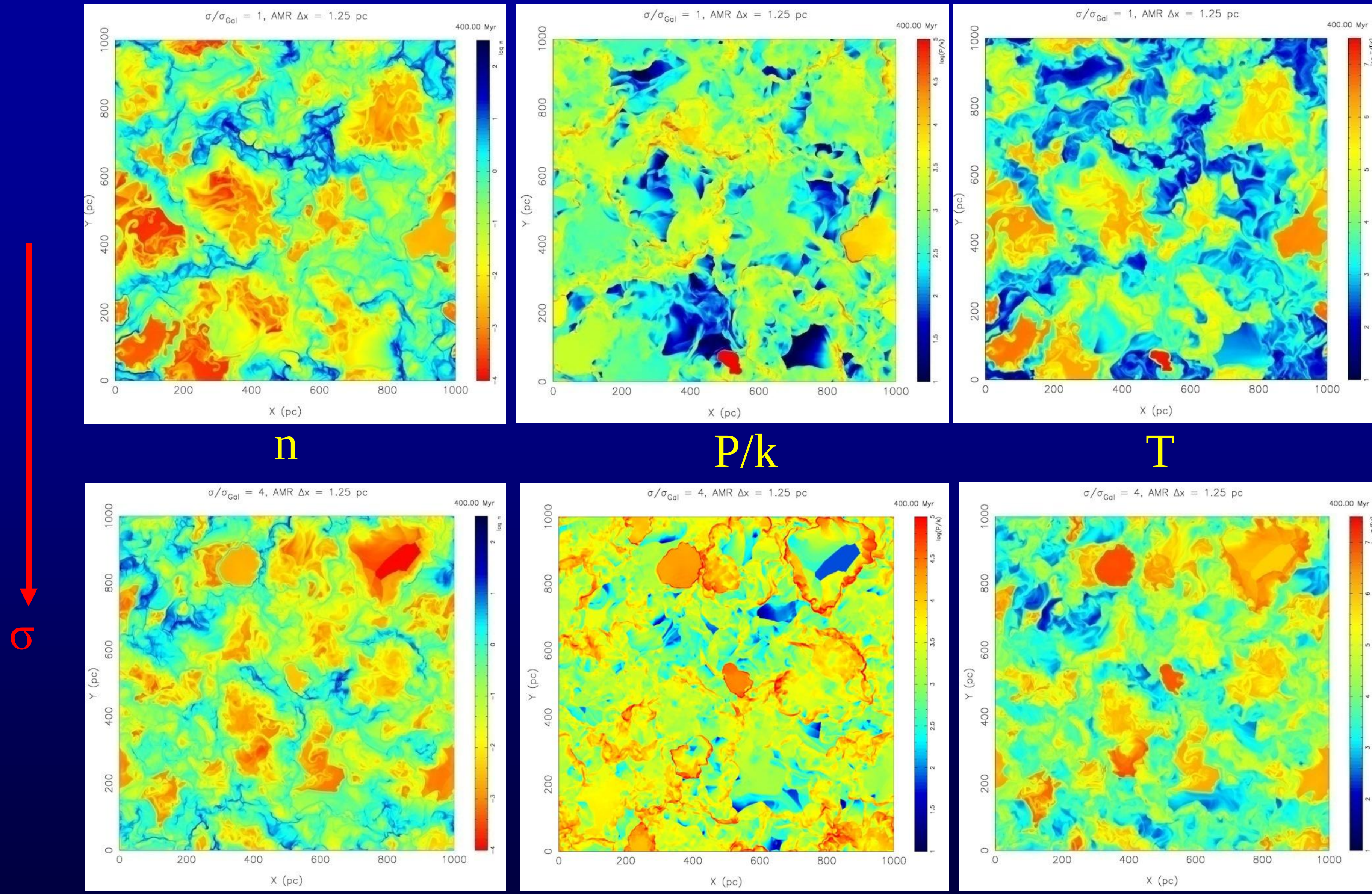


x

y



2D cuts through 3d data cube (disk cut)



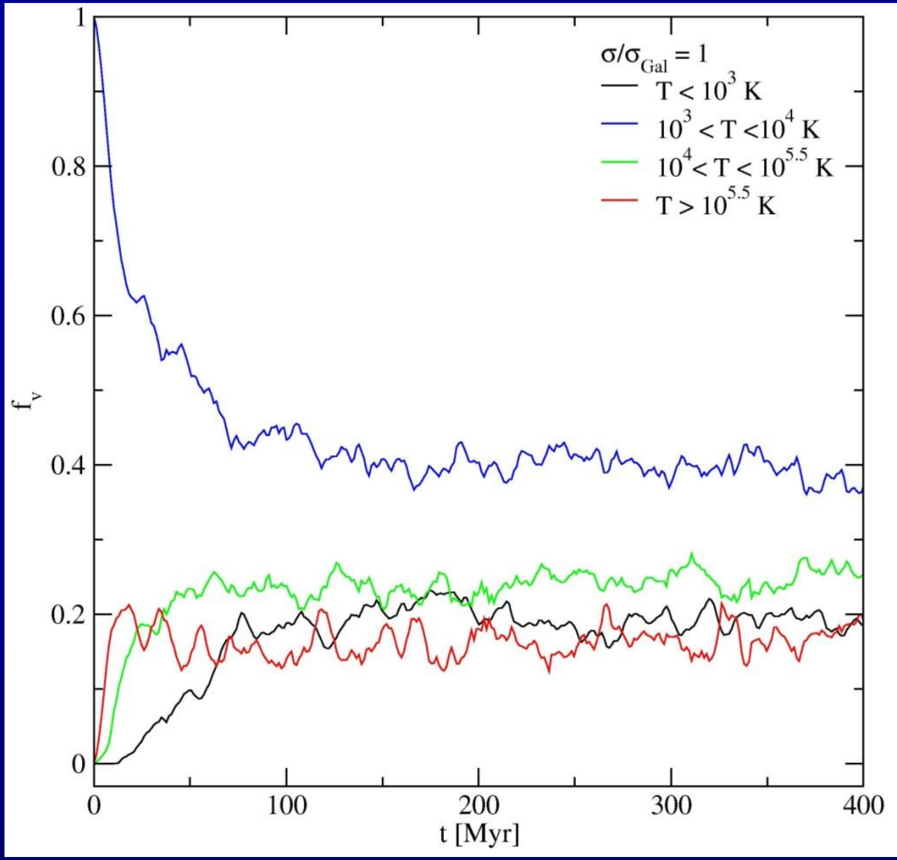
Results

- P/k far from uniform: spatial structure even for high SN rate ($\sigma/\sigma_{gal} = 4$)
- <P/k> ~ 3000 for Milky Way, i.e. much less than canonical values of > 10,000

  Reason: due to fountain flow, average disk pressure can be lowered
- lots of small scale structure: filaments, shock compressed layers → cloud formation

Volume filling factors:

σ/σ_g	f_{cold}	f_{cool}	f_{warm}	f_{hot}
1	0.19	0.39	0.25	0.17
2	0.16	0.34	0.31	0.19
4	0.05	0.3	0.37	0.28
8	0.01	0.12	0.52	0.35
16	0	0.02	0.54	0.44



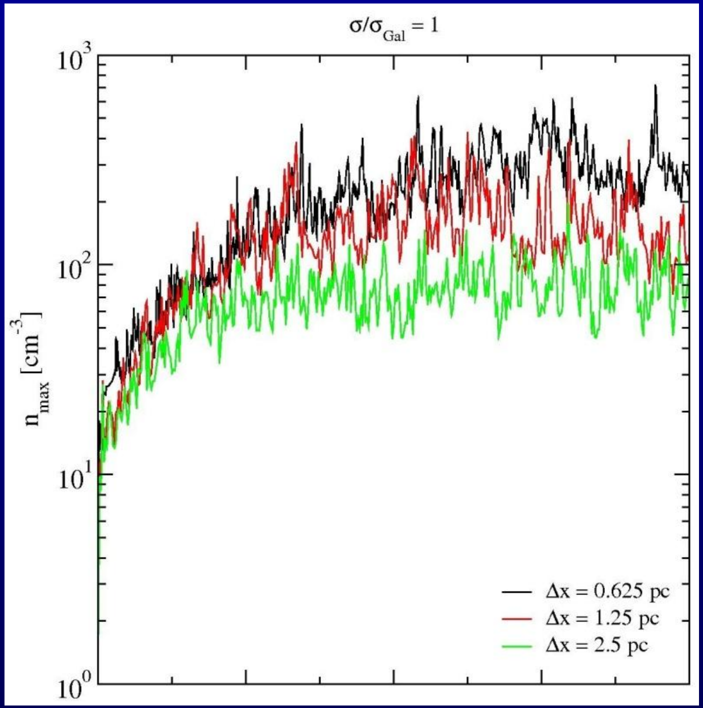
cold: $T<10^3$ K; cool: $10^3 <T< 10^4$ K
warm: $10^4 <T< 10^{5.5}$ K; hot: $T>10^{5.5}$ K

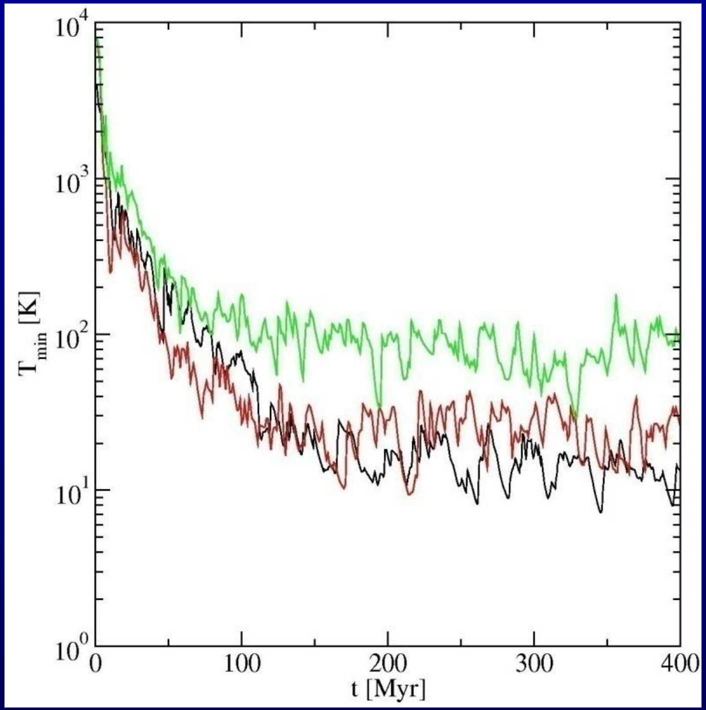
Vff of hot gas is fairly low!
(in agreement with HI holes in ext. gal.)

f_V fairly const. with time for $t > 200$ Myr!
Reason: break-out of SBs and fountain flow acts as pressure release valve!

Can we believe numerical simulations?

→ Necessary Condition: results should be resolution independent!
Look at smallest scales, i.e. T_{min} and n_{max}

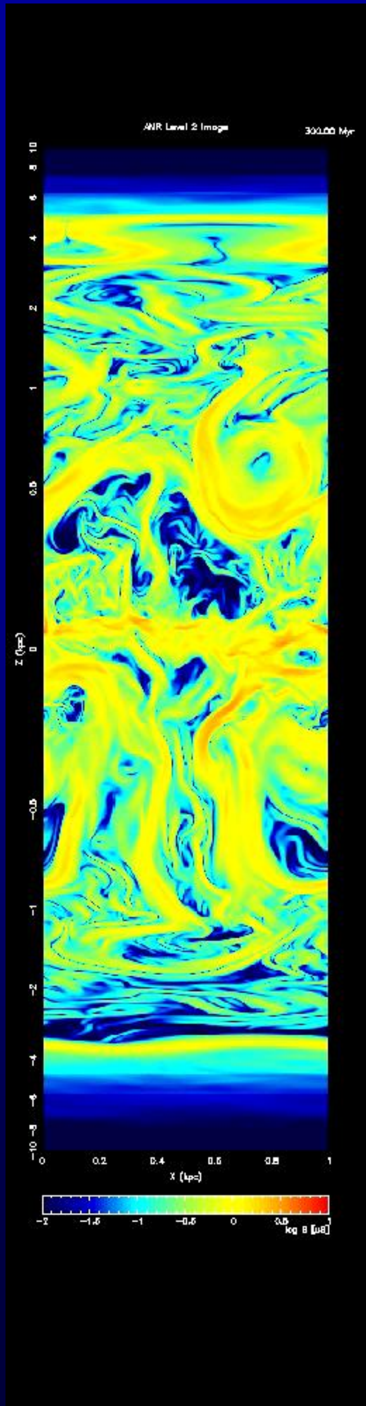


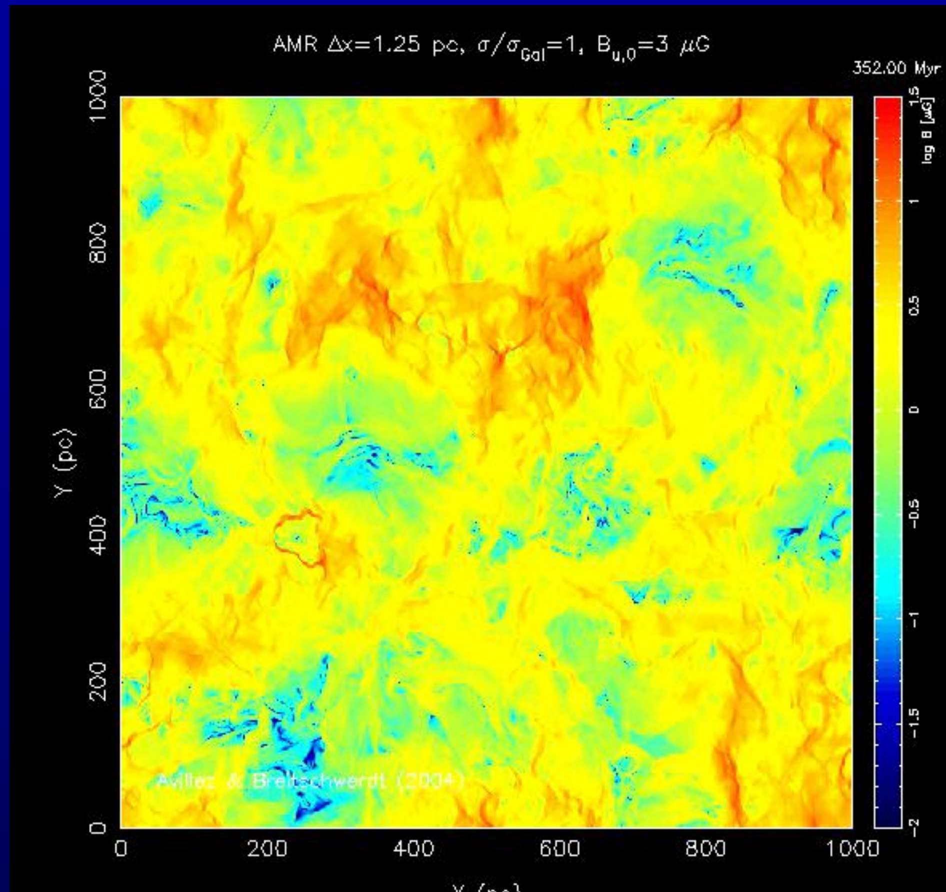


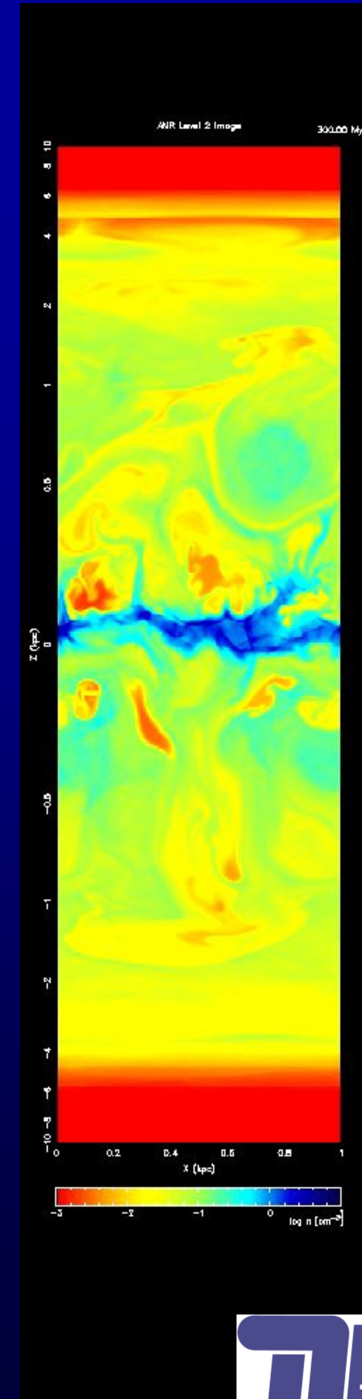
Simulations at different resolution: Δx=0.625, Δx=1.25, Δx=2.5

Convergence at Δx=1.25 (for T_{min} and n_{max}) for the physical processes considered here!

MHD ISM Simulations



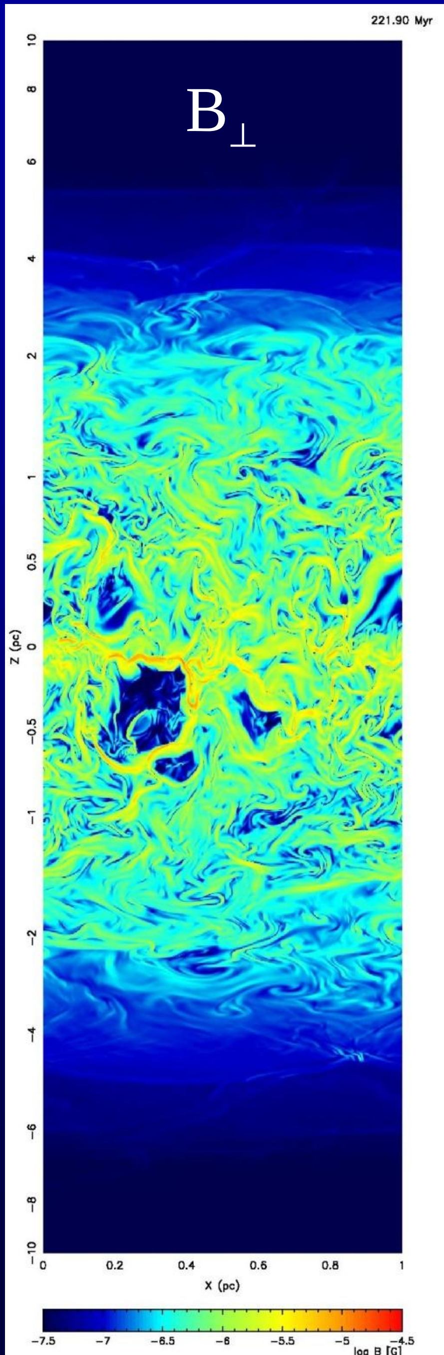




Outflow not inhibited by B-field

→ field lines pushed away

→ loop structure



Presence of B-field

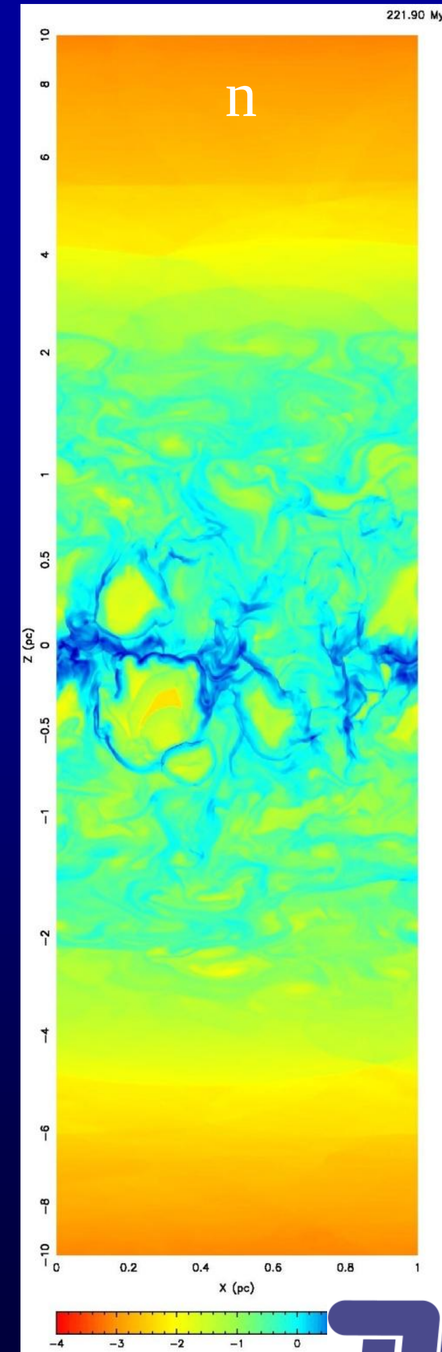
- cannot prevent outflow from disk,
- because in 3D field lines can be pushed aside
  - due to "open" field lines ("coronal holes")
- turbulent dynamo possible

→ pressure release "valves"

- generates large loop structures flow oriented preferentially parallel to B-field

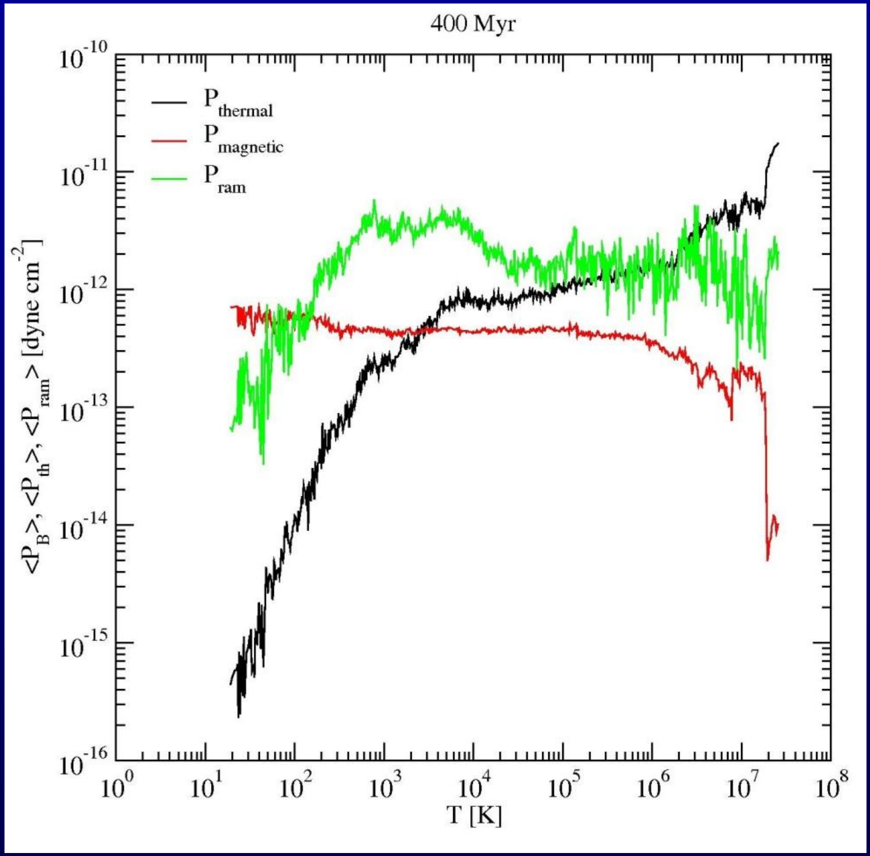
Density field

- halo flow not smooth (clumpy)



Which ISM component controls large scale dynamics?

P_{th}, P_{mag} or P_{ram}??? → calculate average pressures (t=400 Myr)

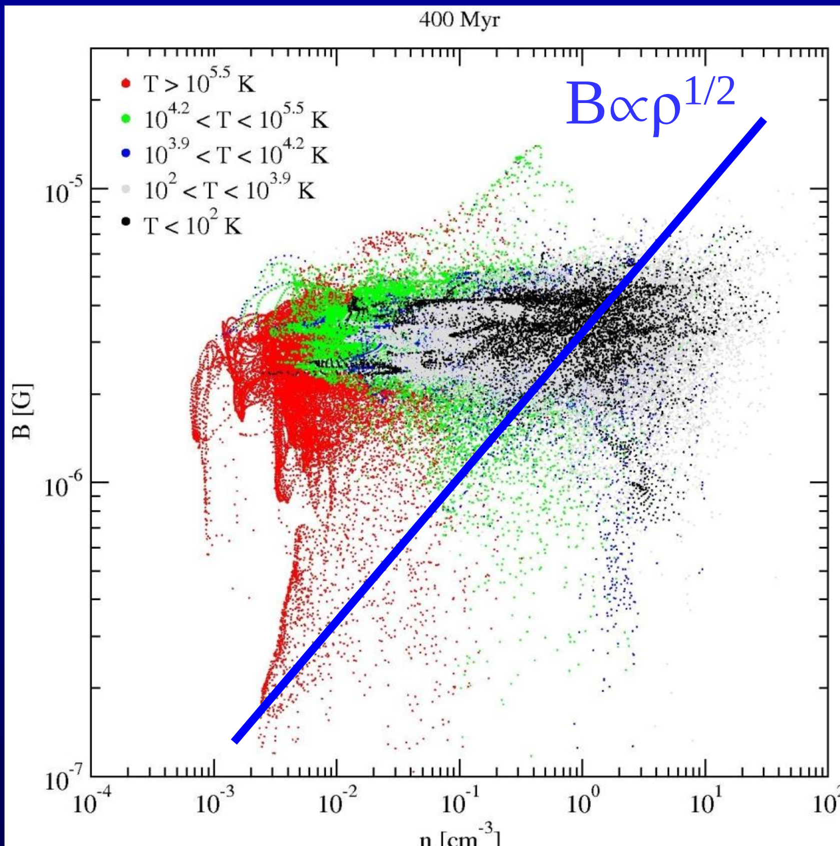


- cold gas dynamics determined by frozen-in magnetic field (T<200 K)
- hot gas ($T>10^{5.5}$ K) controlled by thermal pressure

BUT:

- disk gas is ram pressure dominated over a wide range of temperatures: (10^2 K < T < 10^6 K)
- $P_{mag} \approx$ const. for $10^2 < T < 10^6$ K

Does the field follow the Chandrasekhar-Fermi law?



Chandrasekhar & Fermi (1953) derived a relation between B and ρ

Idea:

Deviation a of plane of polarization of star-light from spiral arm direction due to random motions of B-field induced by gas turbulence

$$\Rightarrow B = \sqrt{(4/3)\pi\rho}\,\frac{v_{turb}}{a} \Rightarrow V_A = \frac{v_{turb}}{\sqrt{3}a}$$

Result: CF law meaningless: in ISM very broad distribution for all temperatures in the (B-n) scatter plot

Why?

- flow is ram pressure dominated
- supersonic/superalfvenic turbulence

Stability of "gas phases"

- Heiles (2001) reports that > 47% of WNM is in a classically unstable phase between 500 – 5000 K
- Our simulations show that in total 40% of ISM mass is unstable
  - 500 < T < 5000 K: ~ 55% of the gas is unstable
  - T > $10^{5.5}$ K: ~10% is unstable

Does this contradict classical thermal stability theory?

Not necessarily, because

- stability of "phases" was derived in a time-asymptotic limit: instability means that cooling time << dynamical time scale
- stable points determined by properties of interstellar cooling curve

However, in a time-dependent dynamical picture things can be different (e.g. Kritsuk & Norman 2002, Gazol et al. 2001)

- shock waves can induce strong heating
- SN increased turbulence can work against condensation (eddy crossing time << cooling time)

Thermal Instability

Classical Theory due to Field (1965)

- criterion can be directly derived from 2nd law of thermodynamics

$$T\frac{dS}{dt} = -(\gamma - 1)L$$ L…net energy loss function (L=0 thermal equ.)

- perturb the entropy S→S+δS and linearize: $\frac{d\ln|\delta S|}{dt} = -(\gamma - 1)\left[\frac{\partial(L/T)}{\partial S}\right]_A$
- Stability, if δS decreases with time, i.e. $\left[\frac{\partial(L/T)}{\partial S}\right]_A > 0$
- Perturb around equilibrium at constant pressure, i.e mechanical equilibrium ($dS=C_p\,dT$) for local condensational modes ($C_p>0$):

$$\left(\frac{\partial L}{\partial T}\right)_P > 0$$

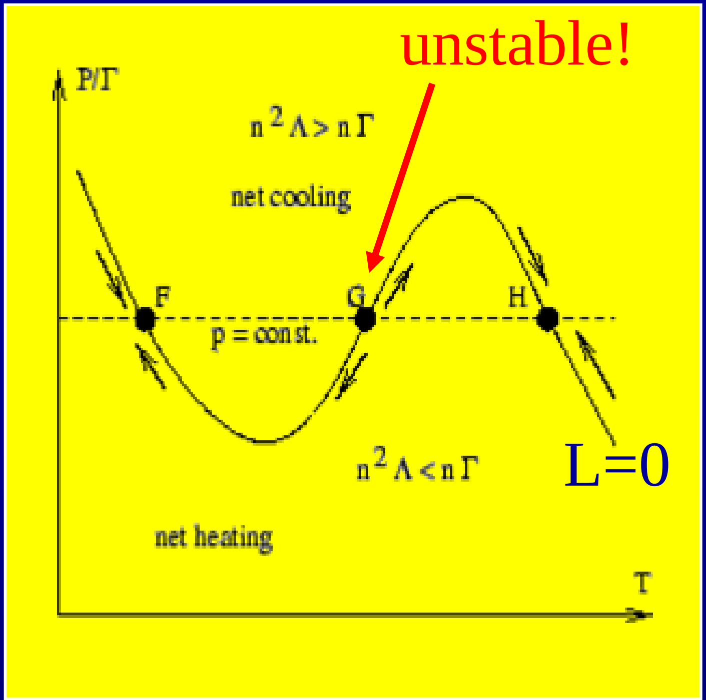
easily violated for standard interstellar cooling functions

- Field criterion does not take into account dynamical processes, e.g. turbulence
- Turbulent diffusion can stabilize, inhibiting local condensation modes (cf. solar chromosphere): $\nu_{turb} \sim Re\ \nu_{mol}$
- Thermal instability inhibited, if fluctuations occur on time scales less than the cooling time: $\tau_{eddy} << \tau_{cool}$

$$\frac{\lambda}{\Delta u} \sim \left(\frac{\rho}{\varepsilon}\right)^{1/3} \lambda^{2/3} < \frac{k_B T}{n\Lambda(T)} \quad (Kolmogorov)$$

$$\Rightarrow \lambda < \left(\frac{k_B \bar{m}}{\Lambda_0}\right)^{3/2} \frac{\varepsilon^{1/2}}{\rho^2} T^{3/4}, \quad \Lambda(T) \sim \Lambda_0 T^{1/2}$$

- incompressible turbulence strictly not true
- for WNM, $\varepsilon \sim 10^{-26}$ erg cm^{-3} s^{-1}, $n \sim 0.3$cm^{-3}, T~1000 K: $\lambda < 10^{19}$ cm

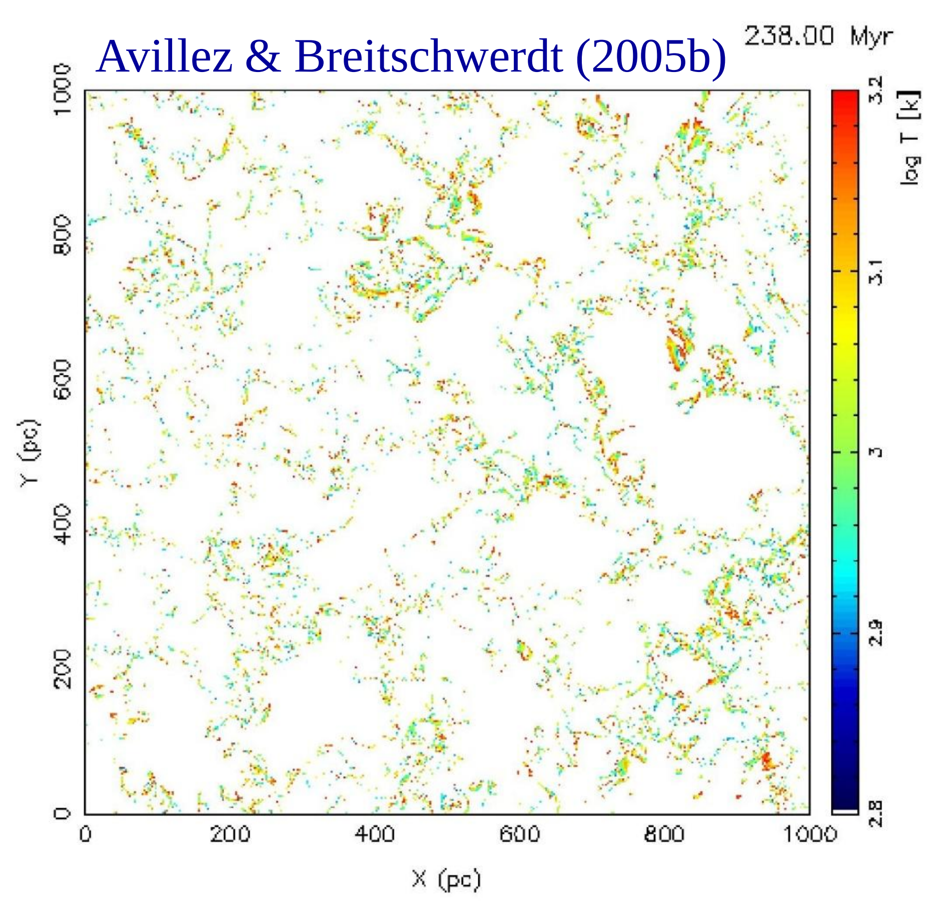


Points F and H are stable
Stability if:

$$\left(\frac{\partial L}{\partial T}\right)_P > 0$$

$$L = n^2\Lambda(T) - n\Gamma$$

Distribution of WNM in the Galaxy



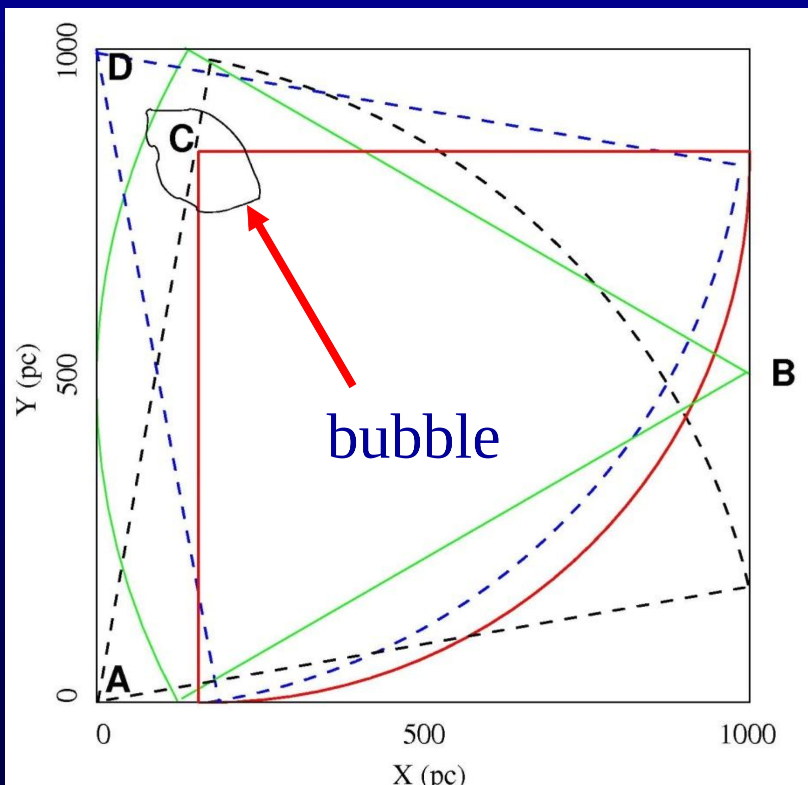
WNM in the unstable regime $10^{2.8} \leq T \leq 10^{3.2}$ K has filamentary structure

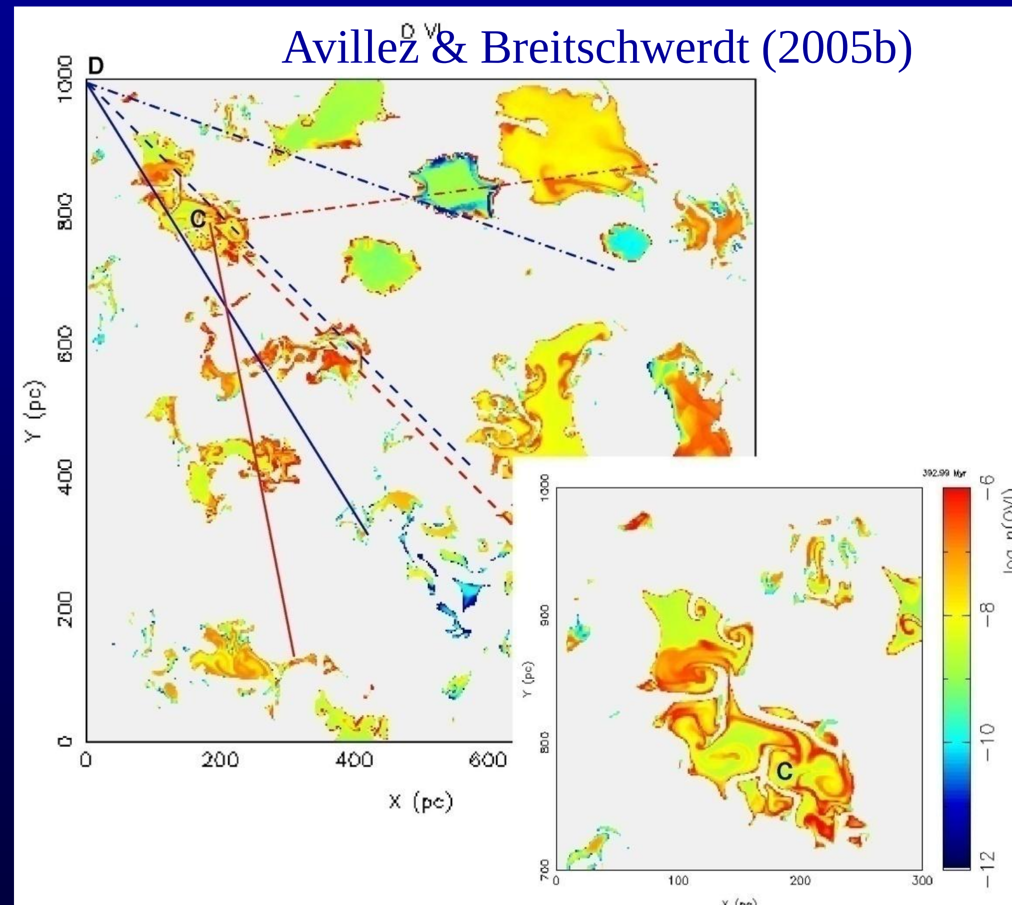
→opposite to MO model

→in agreement with observations (Heiles 2001, Heiles & Troland 2003)

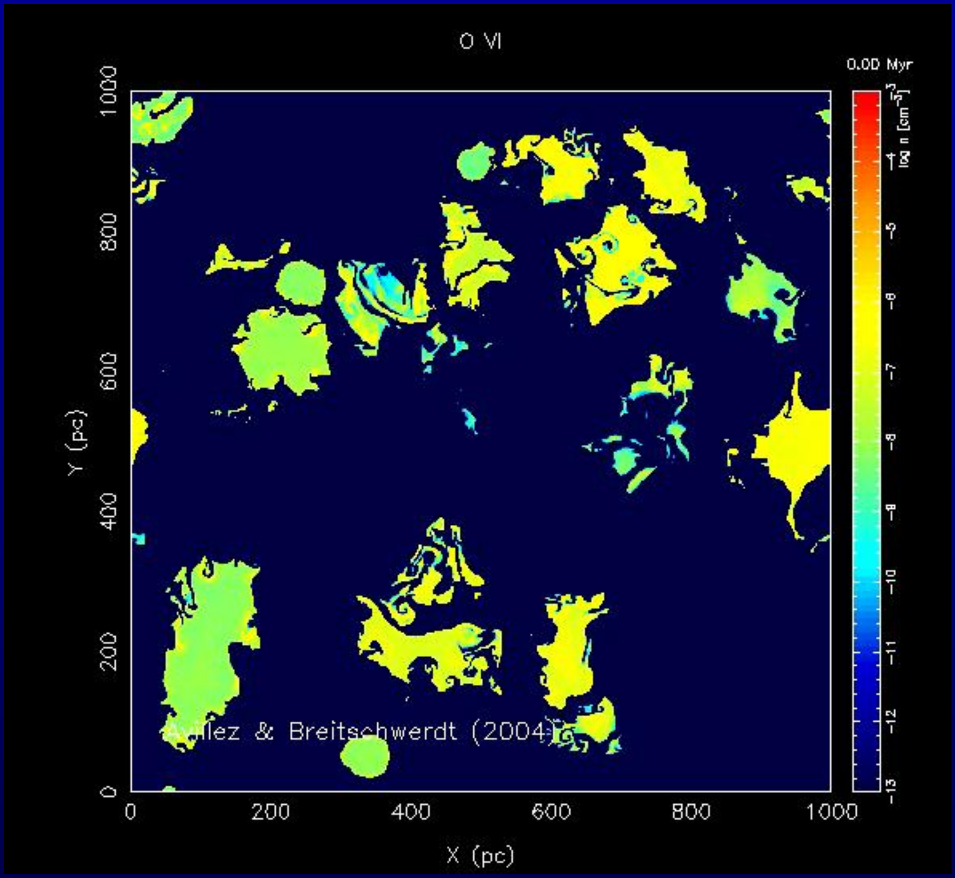
The OVI test: Comparison with FUSE & Copernicus

- OVI traces (cooling down) HIM, not soft X-ray emitting gas!
- OVI produced in conduction fronts? efficiency rather high!
- our simulations show: OVI in turbulent mixing layers!



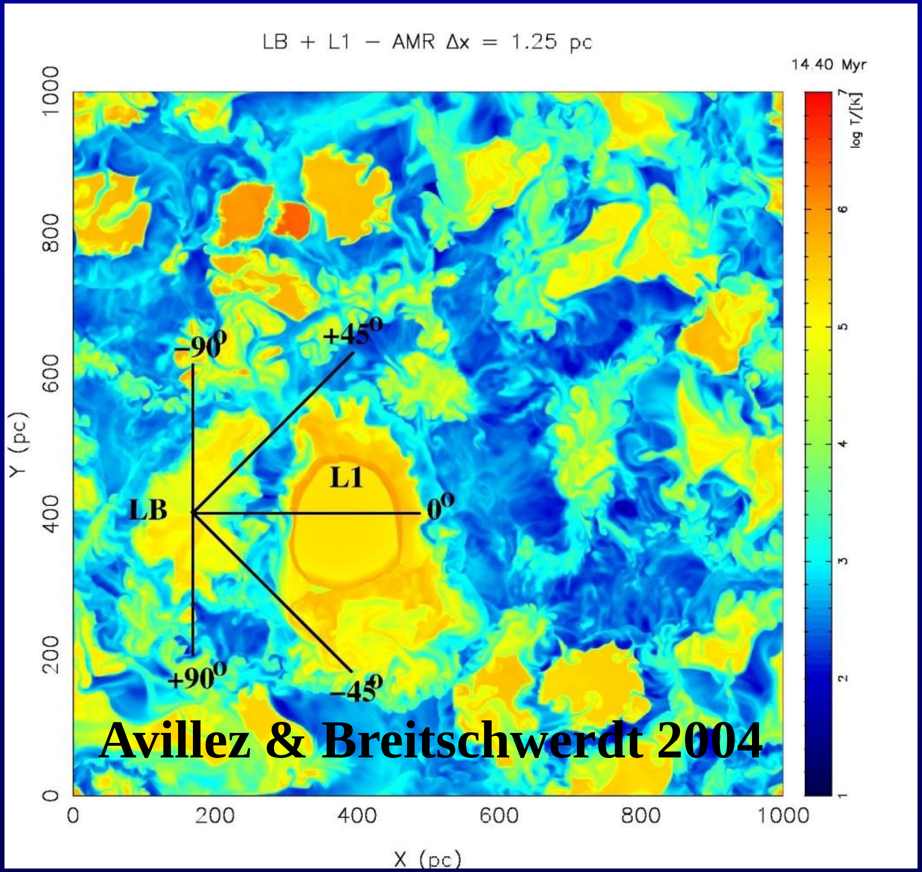


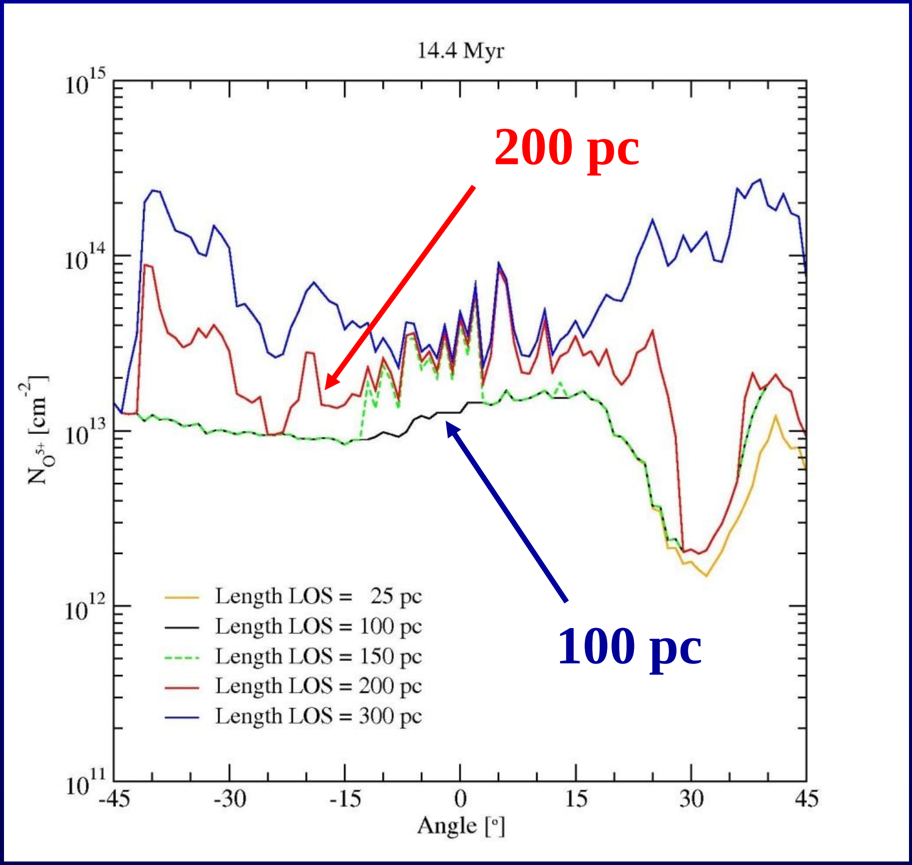
OVI Column densities



- Crucial test for LB models (Cox 2003)
- Reason: previous SNR and SB models generate 10–100 times too much OVI in absorption towards back-ground stars
- Possible solution:
  - ➢ LB is old and has complex temperature structure
  - ➢ Hot gas highly turbulent
  - ➢ Ambient medium inhomogneous

N(OVI) through LB sight lines

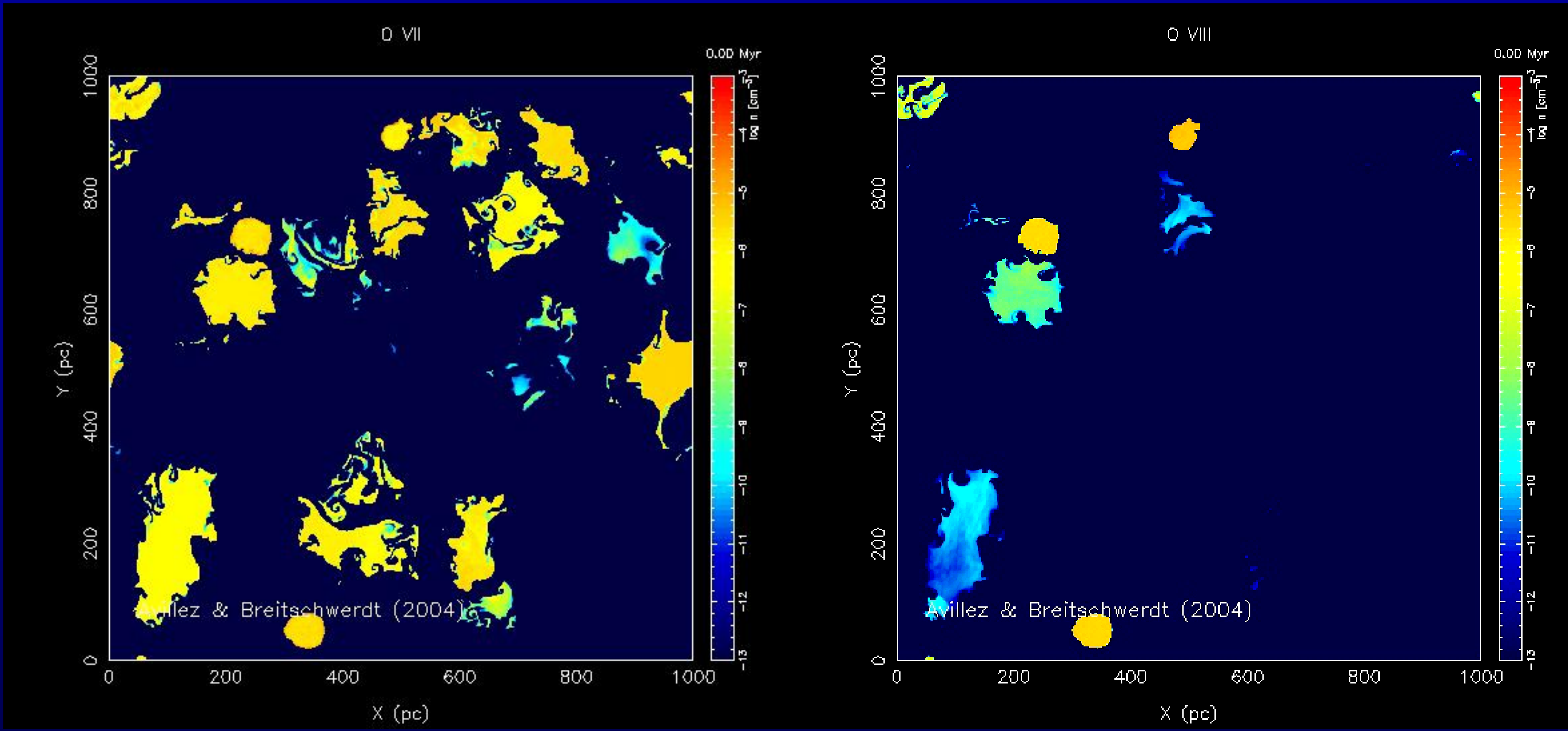




- Temperature map at t=14.4 Myr
- Sampling OVI in absorption

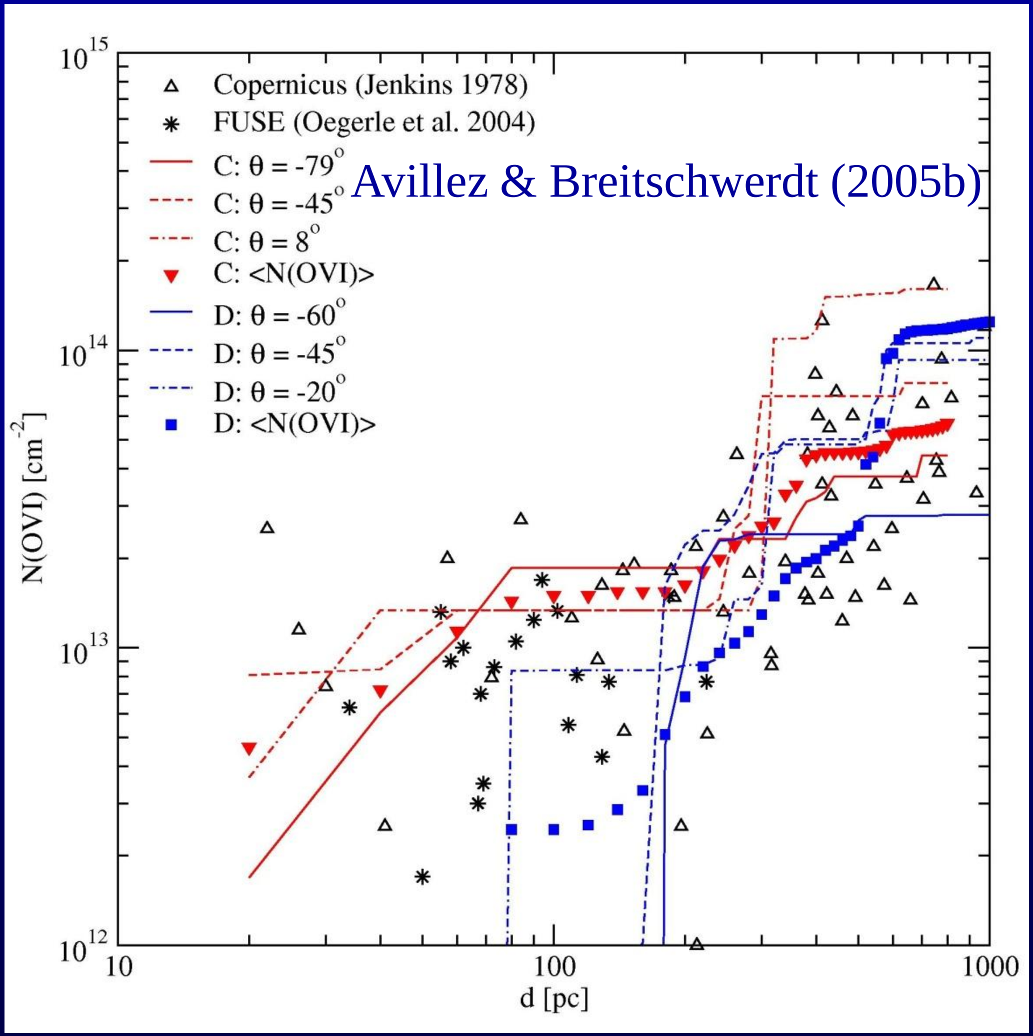
- <N(OVI)> at l=200 pc: ~2×10^{13}cm^{-2}
- Copernicus data: ~1.6×10^{13}cm^{-2} (Shelton & Cox 1994)

… and OVII and OVIII



- OVII traces hot gas during ongoing SN activity

- OVIII is post-supernova tracer
- Loop I higer activity: more OVIII



- FUSE & Copernicus data of OVI absorption lines towards background stars
- comparison with simulations (run for t = 393 Myr): spatially averaged (red triangles, blue squares) and single LOS N(OVI)
- ISM has a pattern, repeating on scales of a few 100 pc!
- **Note:** simulations were done before data of Oegerle et al. (2004) were published!
  No "tuning" of results!

Some Characteristics of Turbulence

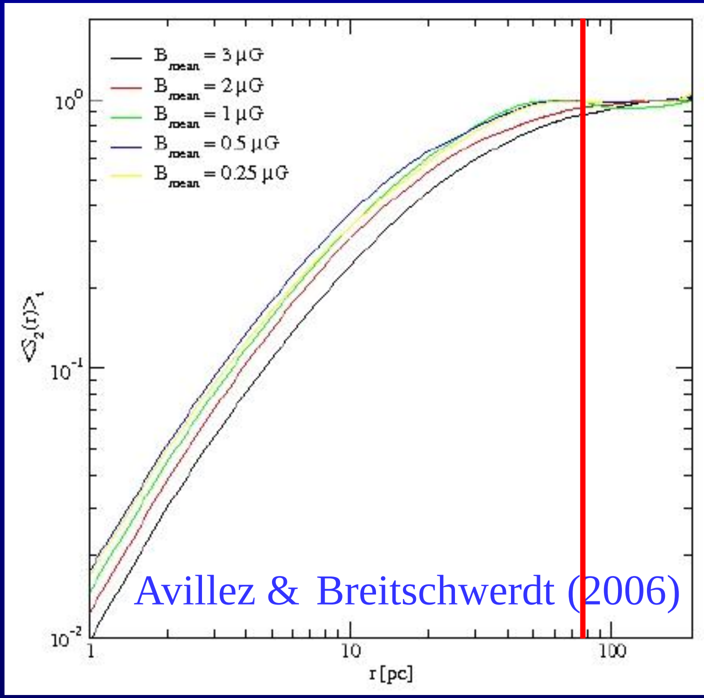
- huge Reynolds numbers $\mathrm{Re} = \frac{uL}{\nu} \simeq 10^6$
- sources: SNe, shear flows → vorticity ω

$$\frac{\partial \vec{\omega}}{\partial t} = \left(\vec{\omega}\nabla\right)\vec{u} + \nu\Delta\vec{\omega}, \quad \vec{\omega} = \nabla \times \vec{u}$$

(from Navier-Stokes equ.)

- structure functions:

$$S_p(l) = \left\langle \left(\delta v_l\right)^p \right\rangle, \ \delta v_l = \left| v(x+l) - v(x) \right|$$

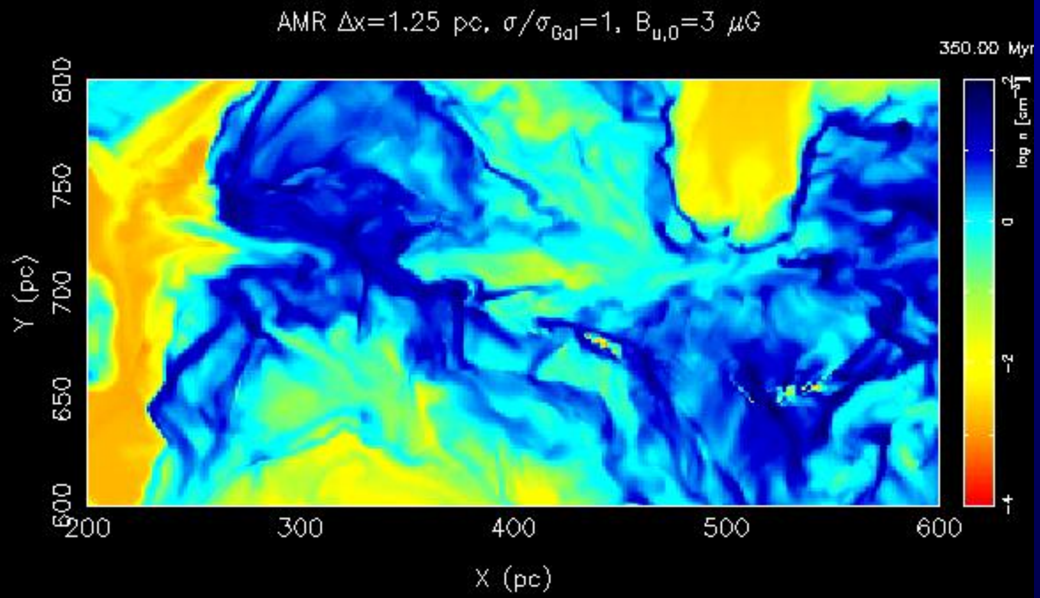


2^{nd} order structure function S_2 flattens at 75 pc → turbulent energy injection scale!
But: smaller scales are possible

- ongoing star formation in late-type galaxies sustains turbulence
- integral (outer) scale: ~ 75 pc (due to SNR's/SB's → "forcing")
- turbulence is 3D and compressible!

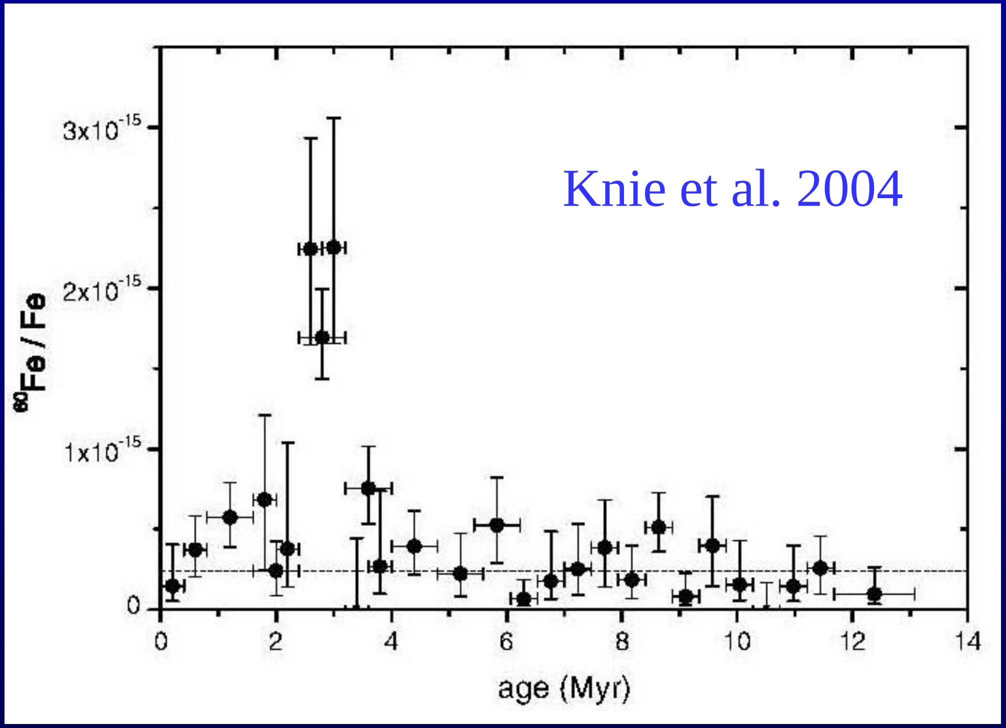
What causes turbulence in clouds?

Avillez & Breitschwerdt (unpublished)



- HI observations show turbulence in starless clouds
- 1.25 pc resolution MHD simulation at t=350 Myr
  → running for 20 Myr
- high level of ISM turbulence due to ongoing star formation
- possibility of driving turbulence for long time
  → external "forcing"
- clouds are **transient** objects
  → filamentary structure
  → partly disrupting cloud

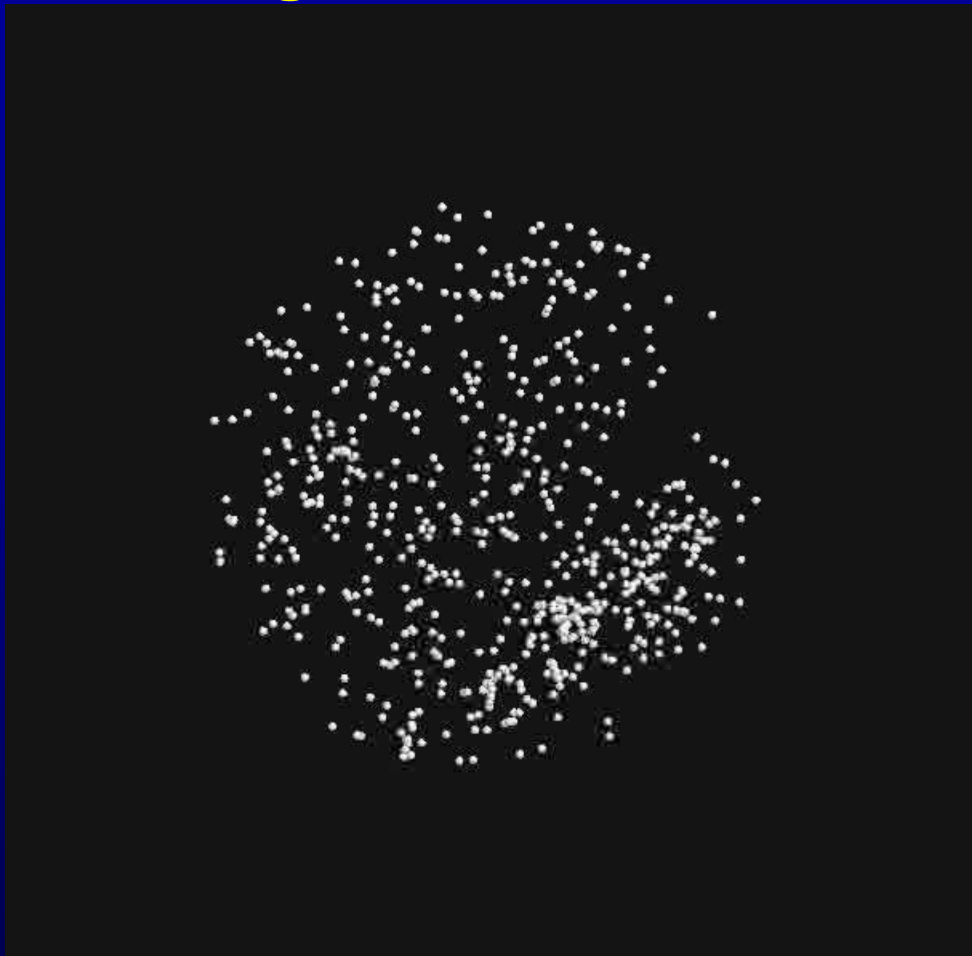
When and where did the closest Supernova near Earth explode?

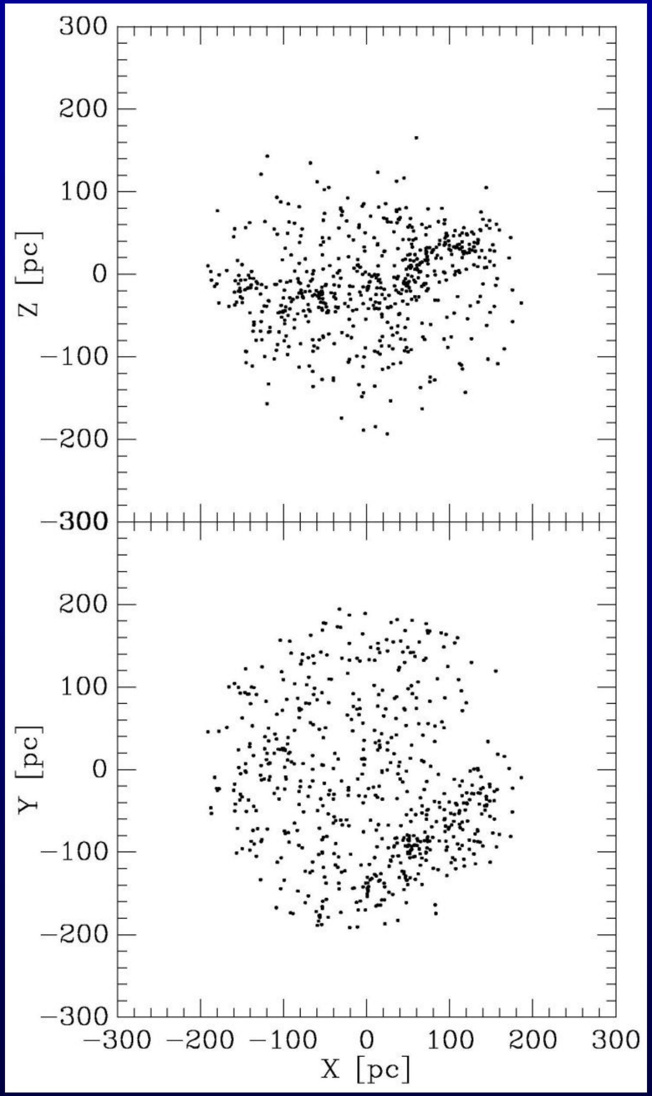


- Measurement of ^{60}Fe/Fe concentration in oceanic ferromanganese crust (Knie et al. 2004)
- dominant source of ^{60}Fe: explosive nucleosynthesis in Type II SNe
- Peak bei t = –2.8 Myr
- Note: also non-zero flux left and right to the peak!

➡ peak and off-peak data points consistent with discovery of a moving group (Fuchs, Breitschwerdt et al. 2006)

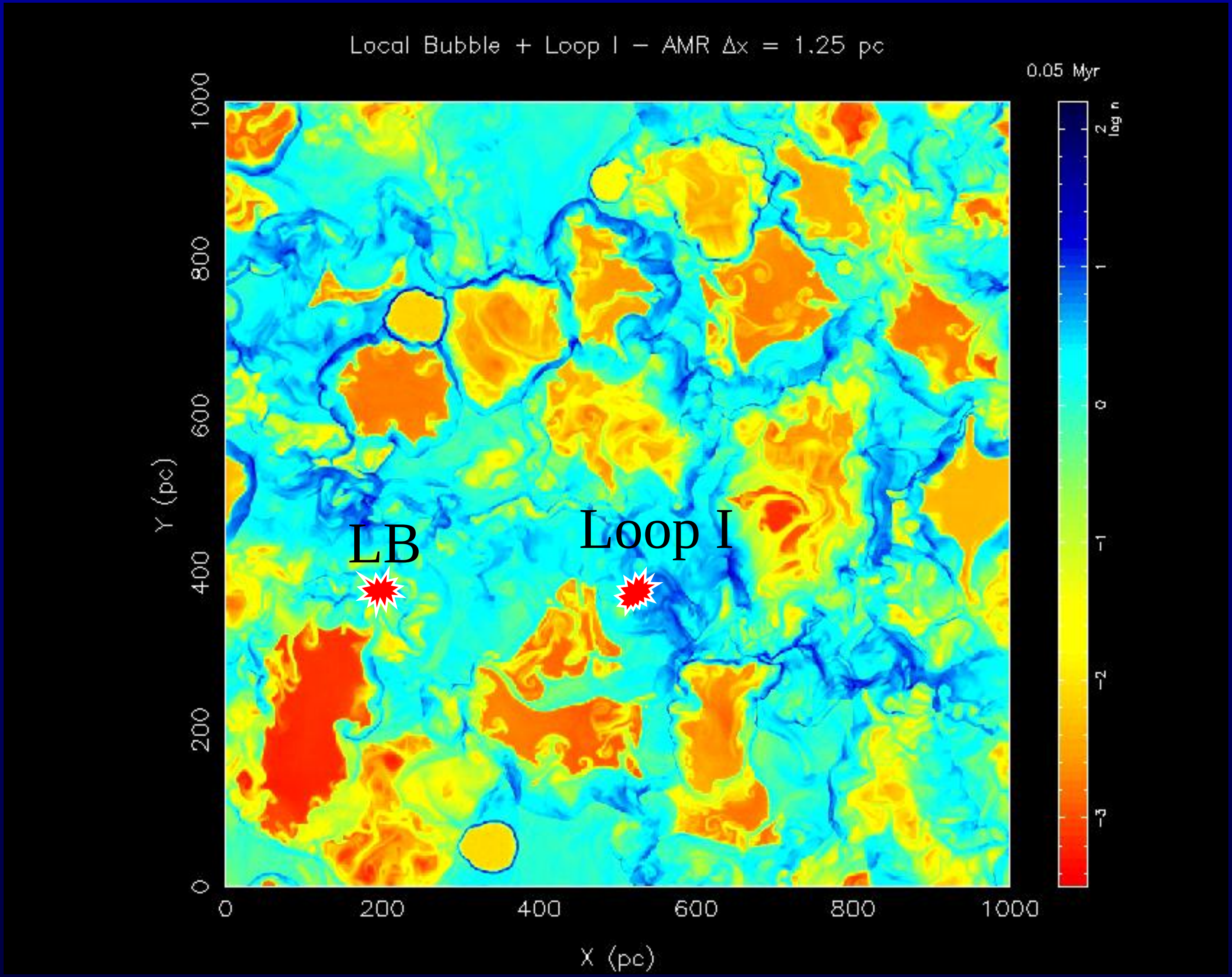
Young stars in the solar neighbourhood





- Positions of 610 stars (400pc vol.) from Hipparcos and ARIVEL catalogues
- 73 stars selected → trajectory calculated

3D AMR Simulations



- Density
- Cut through galactic plane
- LB originates at (x,y) = (200 pc, 400 pc)
- Loop I at (x,y) = (500 pc, 400 pc)

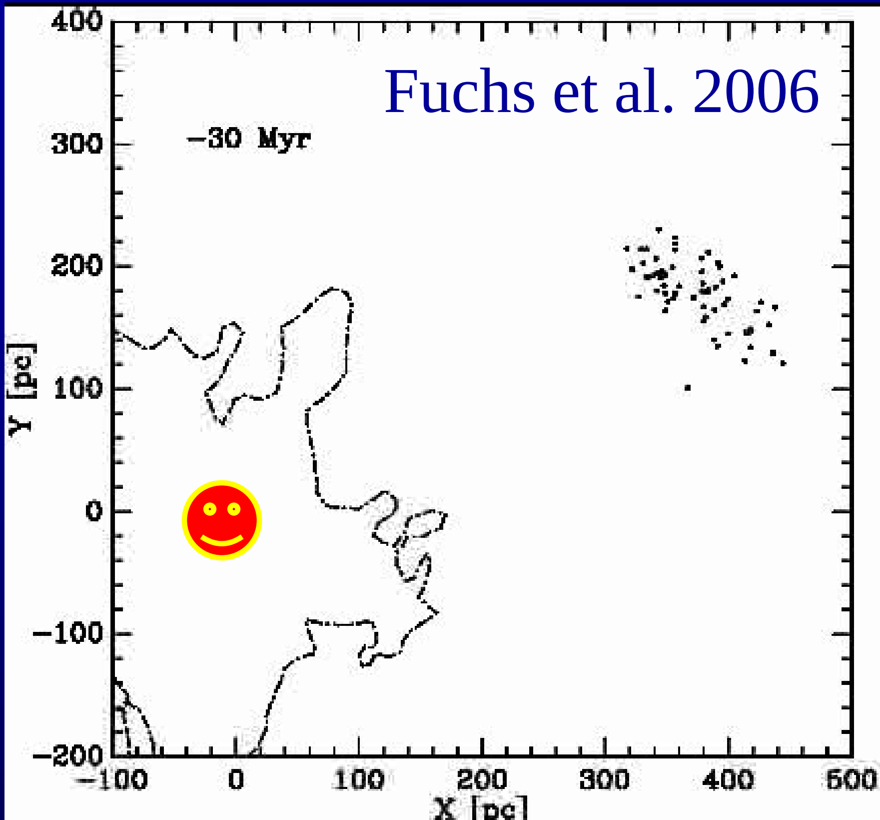
Results

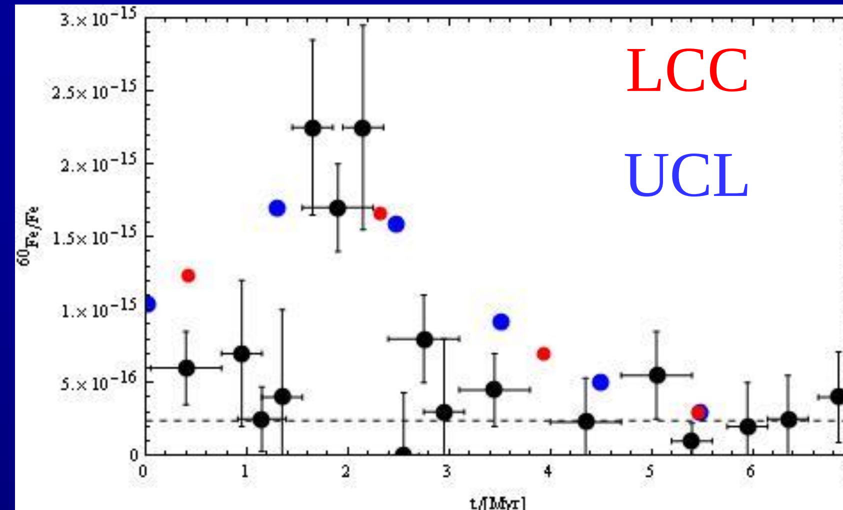
Bubbles collided ~ 3 Myr ago

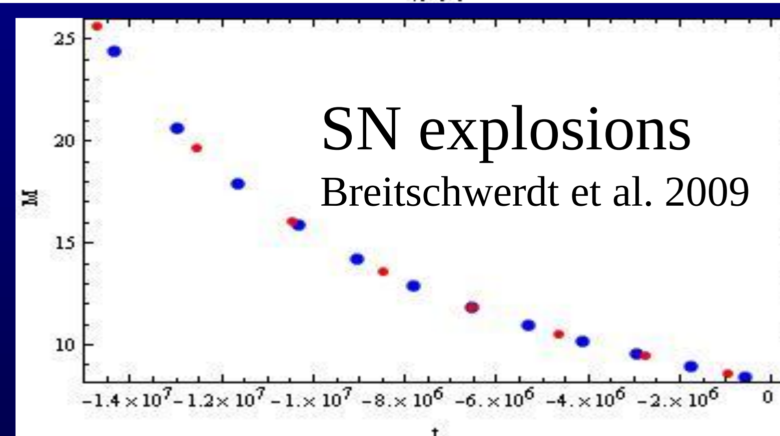
Interaction shell fragments in ~3Myrs

Bubbles dissolve in ~ 10 Myrs

Supernova Explosions in Moving Group of Stars







- Follow stars, calculate mass according to IMF → main seq. life time
- Determine ^{60}Fe yield from stellar evol. Models → natural fit of data!

Summary & Conclusions

- Numerical ISM studies reveal many new features, meaningful if:
  - computational box and evolution times are large enough (i.e. memory effects of initial conditions have disappeared)
  - results are not resolution dependent if $\Delta x \leq 1$ pc (HD)
  - most important phys. processes are included ⇒ selfgravity, CRs…
- SN driven ISM contains structure on all scales → inhomogeneous!
  - ➢ shock compressed layers due to converging flows → clouds
  - ➢ flows are ram pressure dominated and mass loaded
  - ➢ high level of turbulence maintained by SN/SB shock waves
  - ➢ large fraction of mass in thermally unstable temperature regimes, presumably due to strong turbulence
  - ➢ CF law bad description in fast magnetosonic flows
  - ➢ B-field is dynamically less important except for cold gas
  - ➢ turbulence decay law: → conservation of linear momentum?

- FUSE & Copernicus data of N(OVI) reproduced
- Highly turbulent fountain/wind type ISM should favour
  - magnetic dynamo
  - reacceleration of CRs in the disk by 2nd order Fermi
  - reacceleration of CRs in the fountain/galactic wind flow by shocks propagating in the halo (Dorfi & Breitschwerdt 2006)

It is time for a change in paradigm in ISM Theory!

- The End -